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Collapse and recovery of the yellowtail flounder (*Limanda ferruginea*) fishery on Georges Bank

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Abstract

Stock biomass of yellowtail flounder (*Limanda ferruginea*) on Georges Bank was depleted by over-fishing from the 1970s to the mid-1990s, but fishery restrictions have effectively increased survival, and with recent strong recruitment, biomass is rebuilding to historic levels. The decline, collapse and recovery of Georges Bank yellowtail flounder is illustrated by past and present spatial distribution and abundance data from groundfish surveys and trends in exploitation, recruitment, biomass and age composition from recent stock assessments. Evidence for the dominant influence of exploitation on the decline and reduced abundance of this stock and the effectiveness of the current management strategy towards stock rebuilding is illustrated through deterministic simulations and yield per recruit analyses.

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1. Introduction

The yellowtail flounder (*Limanda ferruginea*) is a small-mouthed pleuronectid which generally inhabits sandy substrates in relatively shallow waters (37 - 91 m) of the continental shelf of the western north Atlantic from southern Labrador to Chesapeake Bay (Bigelow and Schroeder, 1953; Scott and Scott, 1988; Collette and Klein-MacPhee, 2002). Tagging observations, larval distribution, life history traits, and geographic patterns of landings and survey data

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indicate that Georges Bank yellowtail flounder comprise a relatively discrete stock (Lux, 1963; Neilson et al., 1986). The management unit recognised by Canada and the USA for the trans-boundary Georges Bank stock includes the entire bank east of the Great South Channel to the Northeast Peak (Fig. 1).

Over-fishing due to intensive exploitation is frequently cited as an important factor contributing to the collapse of marine fish stocks (Hutchings, 2000). The progression of a fishery from an over-exploited condition to a collapsed state involves impairment of the reproductive capacity of the harvested species (i.e. recruitment over-fishing) and often occurs by reduction of the spawning stock biomass. The potential for recovery of a heavily exploited marine fish

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Fig. 1. Map of Georges Bank illustrating the stock management area (bounded by light grey line) for Georges Bank yellowtail flounder, the location of the International Boundary (dashed line) and Closed Area II (bounded by dark grey line). (X-axis: latitude; Y-axis: longitude).

stock is influenced by both environmental conditions and management strategies which promote rebuilding of spawning stock biomass and reduce fishing mortality on incoming year classes. In this paper, we examine the empirical evidence for the decline, collapse and recovery of the Georges Bank yellowtail flounder stock by evaluating trends in spatial distribution and abundance data from research vessel surveys, and trends in exploitation rate, recruitment, population biomass and age structure from recent assessments of stock status. For our evaluation, we define a period of low biomass (1984-1995) and reduced recruitment (1983-1995) as the 'collapsed' period for Georges Bank yellowtail which is bounded by much higher levels of recruitment and biomass before 1983 and after 1995. This definition is also supported by the 1994 analytical assessment which concluded that the Georges Bank stock had collapsed by the early 1990s (NEFSC, 1994). Establishing the causal factors underlying population declines in exploited marine fish populations is challenging because it is difficult to separate the effects of environmentally driven variability from human-induced changes (Fogarty and Murawski, 1998). Through deterministic simulations and yield per recruit analyses, we provide evidence for the dominant influence of exploitation on the collapse of this stock and the effectiveness of the current management strategy towards stock rebuilding.

2. Commercial fishery and management history

2.1. Pre extended jurisdiction (1935-1976)

Commercial exploitation of yellowtail flounder on Georges Bank began in the mid-1930s by the USA trawler fleet, following a marked decline in landings from the winter flounder fishery (Scott, 1954; Royce et al., 1959), and intensified in the late 1940s due to displacement of effort from the declining yellowtail fishery in southern New England (Royce et al., 1959). Catches (which include estimates of discards) increased from negligible levels in the mid-1930s to an average of 16000 t during 1963–1976, when they included modest catches by distant water fleets (Fig. 2).

The International Commission for the Northwest Atlantic Fisheries (ICNAF) was established in 1950 for the investigation, protection and conservation of the fisheries in the northwest Atlantic to obtain maximum sustained catches in this region (Halliday and Pinhorn, 1996). Gear regulations (i.e. minimum cod end mesh size) and controls on total allowable catch (TACs) were the principal management measures used by ICNAF to regulate exploitation, although minimum fish size, fishing effort and closed area/ season regulations were also implemented. Otter-trawl cod ends in the 1950s and 1960s were usually 114



Fig. 2. Catches (including discards) of Georges Bank yellowtail flounder by country, 1935–2001.

mm stretched mesh. This mesh retained yellowtail below the minimum acceptable market size (30 cm TL) and sometimes resulted in more than half of the total catch per trip being discarded at sea (Lux, 1969). By the late 1960s, the Georges Bank yellowtail stock was being exploited at a level greater than that which would result in maximum sustainable yield and it was recommended that the fishery be regulated with its own mesh size regulation and quota (Brown, 1970). Nationally allocated catch quotas were implemented for Georges Bank yellowtail flounder during 1971 to 1976 when total annual catches were set at 16000 t, but these were exceeded in most years. In 1970, a seasonal area closure was established on eastern Georges Bank (initially March through April but later extended to May) to reduce haddock catches during the haddock spawning period when commercial catch rates were highest. While this area closure encompassed an important part of the yellowtail flounder habitat on the bank, it did not reduce annual catches. The measures introduced by ICNAF were difficult to enforce and generally proved ineffective for controlling fishing mortality on Georges Bank yellowtail flounder.

2.2. Post extended jurisdiction (1977 to present)

With the implementation of extended jurisdiction in 1977 to 200 miles, Georges Bank yellowtail flounder was subject to exploitation only by the USA and Canada (although there was no directed Canadian fishery until 1993). By 1978, landings had declined to 6200 t, about the level they remained at until 1984, except for a brief increase to about 11 000 t in 1982– 1983 (Fig. 2). Several management plans were implemented by the USA from 1977 to 1986 and included regulations for minimum cod end mesh size, minimum fish size, seasonal area closures, mandatory reporting, trip limits and annual quotas. However, these control measures still did not reduce exploitation rates on Georges Bank yellowtail and the stock continued to decline.

In 1984, a maritime boundary between the USA and Canada in the Georges Bank/Gulf of Maine area was established by the International Court of Justice. Subsequently, USA catches of Georges Bank yellow-tail flounder declined sharply between 1985 and 1994 (Fig. 2), partly as a result of the loss of access to the

northeastern portion of the bank and partly from a decline stock in size. In 1993, a directed fishery began in the Canadian portion of the management area on the southeastern Flank of Georges Bank (Fig. 1). Prior to 1993, Canadian landings of yellowtail flounder were small, typically less than 100 t with most groundfish effort directed towards cod, haddock and pollock. In 1994 when the fishery for yellowtail flounder was unrestricted 2139 t were landed by the Canadian fleet (Fig. 2).

The USA and Canada informally collaborated to manage trans-boundary Georges Bank fishery resources during the mid to late 1990s, with the goal of rebuilding principal groundfish stocks, including yellowtail flounder. Various amendments and changes to the USA Multispecies Fishery Management Plan occurred from 1994 to 1996 which were relevant to the Georges Bank yellowtail flounder stock. The most effective of these included the implementation of a year-round closure of Closed Area II (Fig. 1), limitation on fishing days-at-sea and further minimum mesh size increases. USA catches have increased steadily from a record low of 316 t in 1995 to 3 792 t in 2001.

In 1995, the Canadian government introduced quota management of the Georges Bank yellowtail resource as the principal measure for regulating fishing mortality. Other management measures included a minimum cod end mesh size, a seasonal area closure extending from 1 January to 31 May, limited entry of participants, 10% observer coverage and 100% dockside monitoring of landed catches. With the introduction of TACs in late 1994, yellowtail landings dropped to 472 t in 1995 against a quota of 400 t (Fig. 2). Canadian landings have increased steadily since 1995 and in 2001 were 2913 t against a quota of 3450 t.

3. Evidence of collapse and recovery

3.1. Spatial distribution

Bottom trawl surveys are conducted annually on Georges Bank by the Canadian Department of Fisheries and Oceans (DFO) in spring and by the USA National Marine Fisheries Service (NMFS) in spring and fall. Both nations use a stratified random design but with different stratum boundaries. Marked changes in the geographic distribution of yellowtail flounder on Georges Bank have occurred over the past 40 years (Fig. 3). NMFS spring and fall survey abundance data from 1963 to 1972 indicate that there were many areas with high concentrations of yellowtail on Georges Bank, particularly along the southern flank and in the central region. During 1973 to 1982, the NMFS survey data showed a contraction of the area where high concentrations occurred and a general



Fig. 3. Distribution and relative abundance (mean weight/tow per 5-minute square) of Georges Bank yellowtail flounder for composite data grouped by 5-10 year periods from annual bottom trawl surveys conducted by the Canadian Department of Fisheries and Oceans (DFO) in spring and by the USA National Marine Fisheries Service (NMFS) in spring and fall. Area sampled is indicated by shading and mean catch is represented by a solid circle, scaled to catch level. The dashed line represents the international boundary between Canada and the USA. (X-axis: latitude, north; Y-axis: longitude, west).

decrease in the frequency of high survey catches. During 1983 to 1992, high survey catches were rare and very localised; most survey tows caught low quantities of yellowtail (if any), indicating that stock abundance was low. DFO surveys conducted during the 1987–1992 period also show low stock abundance, with most of the stock concentrated on the northeastern part of the bank. During the past 10 years (1993–2002), both NMFS and DFO surveys clearly show that stock rebuilding has occurred, with a marked increase in abundance and distribution on the northeastern part of the bank, in Closed Area II and along the southern flank. However, contemporary distributions do not extend over the central region of the bank, as was the case during 1962 to 1973.

3.2. Exploitation, recruitment, and biomass

Information from the commercial fishery has been used in conjunction with fishery-independent research survey data to evaluate the status of the Georges Bank yellowtail flounder resource. Recent stock assessments (1990s to present) have relied on age-structured virtual population analysis (VPA) calibrated with survey indices of abundance. The VPA time series begins in 1973, when reliable sampling information first became available. A non-equilibrium surplus production model (Prager, 1994) has also been used since 1998 to provide an alternative perspective on stock status. Stock assessment results have shown that the instantaneous rate of fishing mortality (F) exceeded the level of maximum yield-per-recruit (F_{max}) since the late 1950s and exceeded all relevant over-fishing reference points until the mid-1990s. The 1994 assessment indicated that the stock had collapsed and that F needed to be substantially reduced to rebuild spawning stock biomass (NEFSC, 1994).

The most recent assessment of stock status (Stone, 2002) confirms the patterns of exploitation, stock abundance and recruitment observed in previous assessments and provides strong evidence of recent stock recovery. The exploitation rate on ages 3 and older (adult population) was very high from 1973 through to 1994 when it averaged 58%, with peaks as high as 78% in 1984 and 1994 (Fig. 4A). Exploitation on age 3+ declined markedly after 1994, following a reduction in effort in the USA fishery (trip limits and permanent closure of Area II) and the implementation



Fig. 4. Estimated trends in (A) adult (age 3+) exploitation rate, (B) recruitment (millions at age 1) and (C) total (age 1+) beginning of year biomass (thousands of metric tons) for Georges Bank yellowtail flounder based on results from virtual population analysis. Trends in total biomass estimated from a surplus production model (C) are shown for comparison. X-axis labels are year for exploitation rate and biomass, and year class for recruitment.

of quotas in the Canadian fishery. Since 1995, exploitation on age 3+ has averaged 23%, and was at or below 20% during 1999–2001. Estimates of abundance for age 1 recruits reveal a period of good recruitment between 1973 and 1982 (average: 36 million recruits), followed by a period of poor recruitment during 1983 to 1995 (average: 12 million recruits) (Fig. 4B). Since 1995, there has been good recruitment with several strong year classes from 1996 to 2000 (average: 46 million recruits). Even though recruitment was high in the 1970s, population biomass (ages 1+) declined from about 32 000 t in 1973 to 13000 t in 1977, increased briefly to 20000 t in 1982 when the 1980 year class recruited, and then declined and averaged 6000 t from 1984 to 1996 (Fig. 4C). With improved recruitment and reduced exploitation from the mid-1990s onward, age 1+ biomass increased by nearly 10-fold from 6000 t in 1995 to 58000 t at the beginning of 2002. Trends in total biomass estimated from the surplus production model (Fig. 4C) are very similar to those from the VPA, even though the production model does not capture the separate dynamic changes that occur in recruitment, growth and exploitation patterns at age.

3.3. Age structure

Temporal patterns in population age structure determined from the VPA were examined for population numbers grouped into three classes: recruits (ages 1– 2), those ages which generally contribute to the fishery (ages 3–5), and older individuals (ages 6+) (Fig. 5). During the period of reduced recruitment (1983–1995), all age groups were present in the population at low levels compared to the maxima observed in each series. The decline in numbers for the youngest ages was relatively abrupt after 1982, and was followed by a decline of ages 3–5 in 1984 and ages 6+ in 1985 and again in 1988. This pattern



Fig. 5. Population numbers for Georges Bank yellowtail flounder, 1973 to 2002, estimated from virtual population analysis (Stone, 2002), aggregated into age groups and standardised to the largest observation in the series. The period of reduced recruitment (1983 to 1995) is indicated between the vertical lines.

suggests a progressive decline in ages, beginning with the youngest ages rather than the oldest, and is contrary to what would be expected if over-fishing was the only cause of decline. The period of improved recruitment after 1996 is indicated by an expected progressive increase in numbers of younger then older fish in the population.

4. Linkage between collapse, recovery and the fishery

4.1. Deterministic simulations

Fisheries management involves regulation of human activities in order to achieve objectives. The course of events can be influenced by fisheries management interventions but it is also affected by external environmental forces that cannot be controlled. It is presumptuous therefore to assume that fisheries management can accomplish much more than molding the course of events that is more generally driven by environmental forces. Nonetheless, it is instructive to investigate to what extent the period of low biomass during 1984-1995 could be attributed to the high fishing mortality rate that prevailed until the mid-1990s. As these are simply exploratory simulations to get an appreciation of the direction and magnitude of effects, introduction of stochastic elements are an unnecessary complication and were not considered. To maintain comparability, we used the natural mortality rate and the observed weight at age from the most recent assessment to conduct forward projection simulations using the standard catch equation. Fishery exploitation pattern at age has varied substantially over the period but without any persistent trend. For the simulations, we assumed partial recruitment to the fishery of 0, 0.3, 0.7 and 1 for ages 1, 2, 3 and 4 or older respectively, reflecting the recent average. In any simulation, a paramount issue is how to handle recruitment. It is generally postulated that recruitment depends on the spawning potential of the stock and on external environmental forces, but the extent to which either of these dominates the outcome remains a matter of active debate. Resolution of this debate is beyond the scope of this work. Rather, the range of response is bracketed by investigating plausible options.

One line of investigation is to assume that the observed recruitment would have been realised regardless of how the stock was exploited. This scenario is based on the premise that external environmental forces are much more dominant in determining recruitment than spawning biomass. It also assumes that fecundity is high enough to produce a sufficient oversupply of fertilised eggs, which will be subject to high, density-independent natural mortality forces. To conduct such simulations, the fishing mortality rate is altered but the observed recruitment time series as estimated from the VPA is maintained without modification. We considered three scenarios of exploitation, including the realized fishing mortality based on assessment results, no fishing and fishing at a moderate fishing mortality rate of 0.25. The results of this simulation indicate that with either moderate or no fishing, the biomass would have increased at the beginning of the period in response to good recruitment and alleviation of fishing intensity (Fig. 6). Similar to the realised trajectory, however, the biomass would have declined to a low level during the early to mid-1990s, as a result of the poor recruitment during the 1980s, before recovering to a higher biomass. Unlike the realised scenario, however, the decline starts substantially later as the population is bolstered by accumulated biomass during the late



Fig. 6. Trends in population biomass for Georges Bank yellowtail flounder from 1973 to 2002 based on simulations using forward projections of the standard catch equation for three levels of fishing mortality. The analysis uses the estimated recruitment time series and the natural mortality rate and partial recruitment vector from recent assessments.

1980s. Further, even under moderate fishing, biomass is always substantially greater than that realised. Under no fishing the biomass always remains above the initial starting level of the simulation.

Another line of investigation is to compare alternative recruitment assumptions under exploitation with a moderate fishing mortality rate of 0.25. Three scenarios were considered: (i) external environmental forces are dominant and the realised recruitment would have occurred, (ii) the spawning potential of the stock is dominant and the predicted recruitment from a stock-recruit relation would have occurred, and (iii), spawning potential and external environmental forces are both important and environmentally modified predicted recruitment from a stock recruit relation would have occurred. Convincing stock recruit relationships are difficult to demonstrate for most marine fish stocks, and the yellowtail flounder stock on Georges Bank is no exception. However, for the purpose of this simulation, any model that describes the observed dynamics and does not predict recruitment outside the range of observation would be adequate. A Beverton-Holt stock-recruit relation was fit to the observed data from the assessment assuming independent, identically distributed errors. The production characteristics from this stock-recruit fit were similar to those obtained from a recent review of reference points for New England groundfish (NEFSC, 2002). Consequently, more sophisticated analyses of error structure and autocorrelated errors were not pursued.

Predictions from this stock-recruit relation were used for the recruitment of scenario (ii). For scenario (iii), it was assumed that the spawning potential effects and the external environmental effects were independent and acted as multiplicative factors. The external environmental effect was measured as the ratio of the observed recruitment to the predicted recruitment in any given year. The environmentally modified recruitment for simulated moderate fishing is obtained as the product of the simulated forecast recruitment and the environmental effect. This approach assumes that whatever external environmental forces occurred in a given year to either reduce or increase recruitment from its predicted value would occur proportionately regardless of variation in the number of fertilised eggs caused by differences in the spawning biomass. This may be somewhat optimistic

if density dependent compensation increases substantially at higher recruitment, but it provides a bound to the response. The analysis shows that a pronounced decline in abundance is evident only under the realised recruitment scenario (Fig. 7), while both the alternative recruitment scenarios result in the biomass fluctuating about a fairly high level. The increase in biomass at the beginning of the simulation period persists longest for scenario (ii), until a biomass close to the equilibrium state for such recruitment dynamics is achieved. Scenario (iii) with combined spawning biomass potential and external environmental forces influencing recruitment had a biomass intermediate between the other scenarios during the late 1980s, but shows a substantial increase in biomass during the late 1990s. This is similar to the biomass increase perceived in the assessment but the simulated biomass is already at fairly moderate to high levels at the beginning of the increase and attains unprecedented heights.

While the evidence for collapse indicates that the period of poor recruitment was environmentally induced to some extent, the deterministic simulations of the transient response of the population suggest that the high fishing mortality rate was a dominant influence for the collapse. If recruitment is entirely determined by external environmental forces and the



Fig. 7. Trends in population biomass for Georges Bank yellowtail flounder from 1973 to 2002 based on simulations using forward projections of the standard catch equation for three scenarios of recruitment. The analysis uses a moderate fishing mortality rate of 0.25, and the natural mortality rate and partial recruitment vector used in recent assessments.

realised recruitment would have occurred regardless of how fishing mortality rate was regulated, then a period of low biomass would have been observed. However, this period of low biomass would have been of relatively short duration and, significantly, the biomass would have remained about two to three times higher even at its lowest level. If, on the other hand, recruitment is dependent on spawning potential, then a lower fishing mortality rate would have resulted in maintenance of high biomass, subsequently leading to higher recruitment during the 1980s than that observed. Considering the results of these two simulations, it is reasonable to conclude that if recruitment is at all moderated by the spawning potential of the resource, regulation of fishing mortality to a moderate level could have completely averted a marked decline in stock size and an extended period of low abundance.

4.2. Per recruit analyses

Yield per recruit (YPR) analyses are useful to fishery resource managers for evaluating the effects of alterations in harvesting activity on the yield from a given year-class or cohort (Gulland, 1983). The common age-based YPR model of Thompson et al. (1931) was applied to Georges Bank yellowtail flounder using assessment results from Stone (2002) to explore whether trends in stock abundance followed patterns expected by these simple models. The 2002 assessment estimates of fishing mortality at age, natural mortality, weight at age, maturity at age, and proportion of mortality that occurs within a year before spawning were used to calculate yield per recruit and spawning stock biomass per recruit (SSBPR). The values for each year were assumed to apply in an equilibrium state for the calculations. While all of these population parameters varied from year to year, the fishing mortality underwent the most significant change and was the principal factor affecting results.

The fishing mortality on ages 4-6 averaged greater than 1.0 for the years 1973 through 1994 and then dropped to 0.10 in 2001, following a trend similar to that depicted in Fig. 4A. This large change in fishing mortality rate did not cause a large change in yield per recruit (Fig. 8A). In contrast, the spawning stock biomass per recruit (SSBPR) has increased 2-4 fold since 1995 due to the recent marked reduction in



Fig. 8. Estimated trends in (A) yield per recruit (YPR) and spawning stock biomass per recruit (SSBPR), and (B), a comparison of age 6+ abundance from yield per recruit analysis (kg) and virtual population analysis (Stone, 2002) for Georges Bank yellowtail flounder, 1973–2002.

exploitation rates (Fig. 8A). This increase in SSBPR is due almost entirely to changes in the plus group abundance; the lower fishing mortality rates allow the plus group to accumulate many more fish than at the high fishing mortality rates (Fig. 8B). The estimated abundance in the plus group from the assessment also shows a large increase in recent years. The lag relative to the per recruit calculations is due to the time needed for cohorts to begin filling the plus group because the per recruit expectations assume the observed F over the lifetime of a cohort, whereas the assessment has annually varying F for each cohort (Fig. 8B). Some of the recent large year classes will only be entering the plus group in a few years, which should cause the plus group to continue to increase if the fishing mortality rate remains low.

The yield per recruit calculations demonstrate the potential benefit to stock biomass of reduced fishing mortality rates. Current fishing mortality is somewhat lower than the fishing mortality rate at which maximum yield per recruit is realised, as evidenced by the slight decline in recent yield per recruit (Fig. 8A). As stock size continues to increase, the number of recruits may increase further, as they generally have since 1996. Thus, significant benefits will have been realised to both the stock and the fishery from the reduction in exploitation rate.

5. Conclusions

Hutchings (2000) conducted an analysis of the recovery time for several heavily exploited marine fish stocks, including Georges Bank yellowtail flounder, and found little evidence of rapid recovery from prolonged declines despite reductions in fishing effort. This appears not to have been the case for the Georges Bank yellowtail stock, which experienced a dramatic decline in abundance through the 1970s, remained at low levels from 1984 through 1995, and then rapidly increased from 1996 to 2002. Our simulation analyses indicate that more stringent regulation of fishing mortality levels during the late 1970s and early 1980s could have averted the rapid decline and collapse of this stock despite the period of low recruitment that occurred from 1983 to 1995. While several regulatory measures have been implemented for the Georges Bank yellowtail flounder fishery since 1950, it was not until 1994, when fishing effort in the USA fishery was significantly reduced through trip limits, gear restrictions and the establishment of a permanent closed area, and in the Canadian fishery through the implementation of TACs, gear restrictions and a seasonal area closure, that exploitation was effectively constrained. These fishery restrictions have increased survival, and with recent strong recruitment, population biomass is rebuilding to historic levels.

Similar to Georges Bank yellowtail, the Grand Bank yellowtail stock was heavily exploited through the 1980s and 1990s and has also responded favourably to management measures that have recently allowed the stock to rebuild. The Northwest Atlantic Fisheries Organization closed the fishery from 1995 to 1997 because of a marked (>50%) decline in stock size from 1990 to 1994. As well, unreported catches were occurring outside the 200 mile limit and overlapping cod and plaice stocks were also in decline. Management measures in recent years which have included TACs based on reduced F (2/3 F_{MSY} target) have led to a rapid increase in the stock, with stock biomass now estimated to be above B_{MSY} (Walsh et al., 2002). In contrast, the southern New England stock and the overlapping mid-Atlantic stock both remain over-exploited and at low biomass levels (NEFSC, 2000) despite the implementation in 1994 of a permanent closed area (Nantucket Lightship Closed Area) to reduce fishing mortality and protect yellowtail concentrations within these areas (Fogarty and Murawski, 1998).

In summary, while environmental factors may have contributed to reduced recruitment during 1983– 1995, it is clear that the high fishing mortality rates were a major factor in causing the stock decline and very low population sizes from 1984 to 1995. Furthermore, management measures aimed at reducing fishing mortality rate since 1994, achieved through a combination of TACs, increased mesh size, areaseason closures and effort regulations, have played a significant role in rebuilding the Georges Bank yellowtail flounder stock. In contrast to the pessimistic prognosis of Hutchings (2000), some yellowtail flounder stocks have demonstrated a capacity for rapid recovery.

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